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Impacts of Photovoltaics and Electromobility on the Singaporean Energy Sector

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Abstract

Singapore has a steady rise in its electricity demand. The Singaporean electricity supply system relies so far heavily on fossil fuels, especially gas and oil, which are both mainly imported from Malaysia and Indonesia. This makes the electricity system in Singapore rather vulnerable to price variations and possible political conflicts with neighbouring countries. A short term solution is the construction of a LNG (liquefied natural gas) terminal which opens supply options to many sources in the world. In the long term, renewable energies such as photovoltaics will certainly be introduced into the Singapore's energy system in a more significant way. This paper discusses the possibility to produce substantial amounts of electricity by solar photovoltaics (PV). In addition, the integration of electromobility in Singapore is analysed. Using PV and electric vehicles (EV), the future primary energy demand and CO₂ emissions in Singapore could be reduced significantly. The paper will describe the TIMES (The Integrated MARKAL (Market Allocation) EFOM (Energy Flow Optimisation Model) System) model for Singapore which is developed within the project TUM CREATE (Technische Universität München Campus for Research Excellence and Technological Enterprise). TUM CREATE is a research programme sponsored by the Singapore National Research Foundation (NRF). One research goal of a sub-project in TUM CREATE is to develop scenarios of the future energy demand and energy supply in Singapore under various boundary conditions, especially oil and gas prices or policies to reduce import dependencies etc. All upstream and downstream sectors of the energy system, including traffic and heavy industry like refineries, will be part of the developed model. First results about the impact of PV and electromobility on Singapore's primary energy demand and CO₂ emissions are presented here.

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1. Introduction

Singapore is located in South-East Asia. The city-state is placed in the most southern point of Thai-Malay Peninsula and is surrounded by the neighbouring countries Malaysia and Indonesia. Both Straits of Johor and Singapore Strait are natural barriers to Singapore's bordering countries. Despite its relatively limited land area of only about 710 km², Singapore is an exceedingly urbanised and industrialised country on the Asian continent. Total population amounts to about 5 million people, of which more than 1 million are non-residents. Therefore, with over 7,250 inhabitants per km² Singapore belongs to the most densely populated countries in the world. In 2010, Singapore's total gross domestic product (PPP) increased to USD 291.9 billion, equivalent to USD 57,500 per capita [1].

Because of a high level of industrialisation, a still increasing population and the need for air conditioning due to its location in the tropics, Singapore has a steady increase in its energy demand, especially in its electricity demand. Across the country, high-demand areas and points of high energy consumption can be found, such as Singapore's Changi Airport in the western part, the Central Business District in the city centre or the Port of Singapore, one of the busiest container ports in the world.

Due to Singapore's scarcity of indigenous fossil fuel sources, oil and gas have to be imported via pipelines from the neighbouring countries Malaysia and Indonesia to meet the economy's domestic energy demand. In 2008 total primary energy supply in Singapore was 24,788 kilotonnes of oil equivalent (ktoe), of which 18,485 ktoe was from oil and 6,167 ktoe from gas. The total final energy consumption after conversion losses added up to 16,129 ktoe [2]. Singapore's entire electricity consumption amounted to nearly 41.2 TWh in 2010; most of the electricity was generated by thermal power plants using combined cycle gas turbines, steam turbines, open cycle gas turbines and incineration. So the fuel mix for electricity production in Singapore is mainly characterised by natural gas (~ 79 %), petroleum products (~ 19 %) and marginally by synthetic gas, diesel oil and waste (~ 3 %). In total Singapore's power generation capacity was 10 GW. That means that there is much more capacity available than needed, even for peak demand (about 6.5 GW in 2010) [3]. In 2008 the overall CO₂ emissions in Singapore added up to about 54 Mt. Since the last decades Singapore's CO₂ emissions have been continuously increasing [1].

Because of the fact that Singapore has no indigenous fuel sources, renewable energies such as solar or even tidal or wave energy could play an important role in Singapore's future. Renewable energies will challenge the existing power system. They can contribute to reduce Singapore's CO₂ emissions significantly, especially in conjunction with electromobility.

This paper proceeds in the following way: The methodology of the developed simulation model is described in Section 2. The presentation and discussion of simulated results is done in Section 3. We analyse both the fuel saving and emission reduction potential of PV and electromobility in various scenarios. Finally a conclusion is drawn in Section 4.

2. Methodology

To analyse the effects of the integration of PV and electromobility on the Singapore's energy sector and to generate future energy demand and energy supply scenarios for Singapore, the model generator TIMES is used.

TIMES acts as an economic model generator. It can be used for multi-regional, national or local energy systems and was developed within the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA).

Using this mathematical optimisation model, the development of energy systems over a long-range time horizon can be estimated. The model generator is implemented in the equation-oriented modelling environment GAMS (General Algebraic Modelling System).

An arbitrary energy system can be modelled as a network consisting of processes (power plants, refineries, electric vehicles etc.) and commodities (energy carriers, passenger kilometers etc.). Such a network is called Reference Energy System (RES). Singapore's energy system described by equations is then optimised with regards to a defined objective function. In the case, for example, of a cost-optimised solution, the objective function describes the total costs of the energy system in the period considered.

As additional variable, several boundary conditions like energy prices and policies to reduce emissions or import dependencies can be defined in TIMES. Input parameters for the simulation model are besides past investments (existing power plants etc.) projections for energy prices and energy demand. Furthermore, new technologies and their characterising parameters (lifetime, efficiency etc.) can be part of the model generator.

Figure 1 shows a schematic overview of the developed Singapore model using the model generator TIMES.

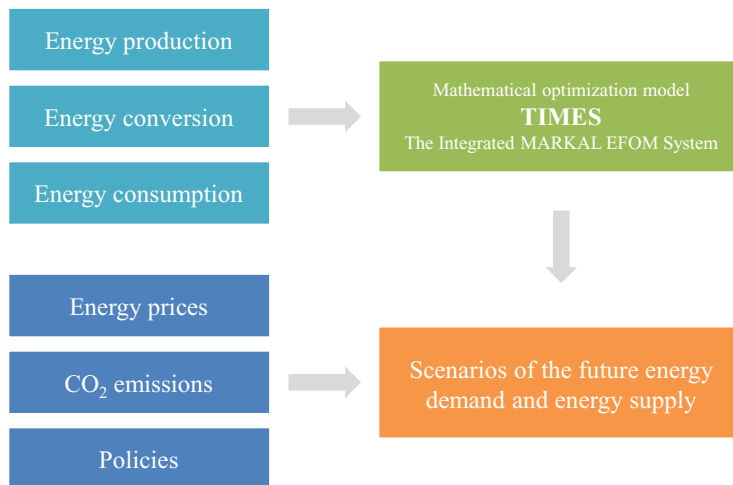


Fig. 1. Schematic representation of the developed model for Singapore: The mathematical optimisation model based on TIMES covers all energy production, conversion and consumption sectors. The model is used to develop scenarios of the future energy demand and energy supply in Singapore under various boundary conditions such as energy prices, CO₂ emissions, policies etc.

As a result of the mathematical optimisation, the potential utilisation of technologies (power plants, electric vehicles etc.), necessary energy generation, costs of the energy system or CO₂ emissions in Singapore will be shown.

3. Results and discussion

3.1. Fuel saving potential of PV

In order to discuss the future composition of Singapore's grid mix by implementing PV, it is necessary to define a baseline scenario which is based on past and current developments. It is assumed that the future electricity demand in Singapore will grow with an annual rate of 3.2 %. This assumption is supported by Singapore's growth rates in its electricity demand over the past 30 years (1978-2008).

According to Fig. 2 (a), Singapore's electric energy consumption will be fully covered by gas fired power plants as from the year 2020. The existing oil power plants will only be used until their decommissioning. Thus, the percentage of electricity generation by oil is projected to decrease to zero until 2020 due to higher overall costs in comparison to gas plants. These results are derived from the TIMES simulation and are based on various studies published by the International Energy Agency and the PA Consulting Group [4, 5].

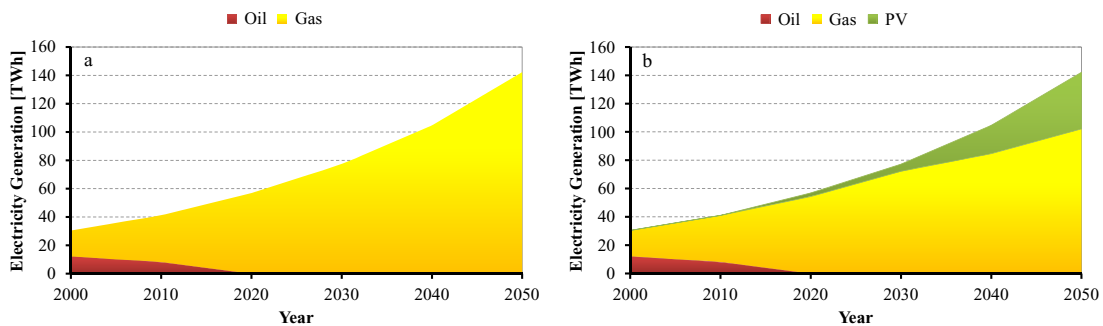


Fig. 2. (a) Electricity generation in the baseline scenario: Singapore's future electricity demand will be solely covered by gas fired power plants as of 2020. The existing oil power plants will be phased out. (b) Electricity generation in the PV scenario: A substantial amount of electricity will be generated by photovoltaics starting in 2020. In the year 2050 about 28 % of total electricity generation is based on solar photovoltaics.

The electricity generation of the second modelled PV scenario is shown in Fig. 2 (b). It is predicted that a significant share of power generation is based on photovoltaics. Its power feed will start in 2020 with 2.5 TWh and could rise up to 40 TWh in 2050. Consistent with this, 28 % of total electricity generation is covered by photovoltaics in the year 2050. Today, 4.8 GWh of electricity are generated in Singapore from an installed PV capacity of about 4 MW [6]. According to the TIMES calculations, an installed PV capacity of approximately 32 GW would be necessary to meet Singapore's domestic electricity demand in 2050.

However, photovoltaic systems are not capable of substituting conventional generation capacity. This fact is due to PV's high dependence on weather conditions and the absence of adequate storage systems for electricity. Therefore, these kinds of systems are only able to work as fuel savers in a country's power plant mix. Fuel savers contribute to electricity generation by producing electricity whenever it is possible and avoid usage of conventional power plants and fossil fuels in these periods. This specific behaviour could reduce Singapore's amount of gas and oil imports from Malaysia and Indonesia significantly. The dampening effect on Singapore's import dependency on fossil fuels can be seen in Table 1.

Table 1. Reduction of primary energy demand of electricity generation: The highest savings of about 28 % are reached in 2050 at maximum electricity generation by photovoltaics.

Primary Energy Demand	Baseline Scenario [TWh]	PV Scenario [TWh]	Deviation [%]
2010	81	81	0.0
2020	96	92	4.4
2030	127	119	6.5
2040	172	139	19.1
2050	233	168	28.1

As expected, the main savings in primary energy demand (28.1 %) are reached at maximum photovoltaic generation in the year 2050. Another positive aspect of that scenario is the reduction of carbon dioxide emissions. Based on the model, CO₂ emissions for electricity generation decline by 28% from 51.3 Mt to a level of 36.9 Mt in 2050 compared to the baseline scenario without PV integration.

3.2. Emission reduction potential of PV in consideration of electrified passenger transport

For a deeper discussion about future CO₂ emissions it is essential to take into account large upcoming electricity consumers in Singapore. Hence, electromobility is integrated into the simulation for the third analysed scenario (EV scenario). On the one hand, electromobility holds the potential to reduce the amount of emissions caused by the traffic sector considerably, but on the other hand it increases the emissions caused by additional electricity generation using fossil fired power plants. This scenario expands the PV scenario by considering the transport sector in Singapore. Therefore, a short overview about the passenger transport sector and its future development is given first. Figure 3 shows the simulated final energy demand of passenger transport in Singapore both for the baseline and the EV scenario.

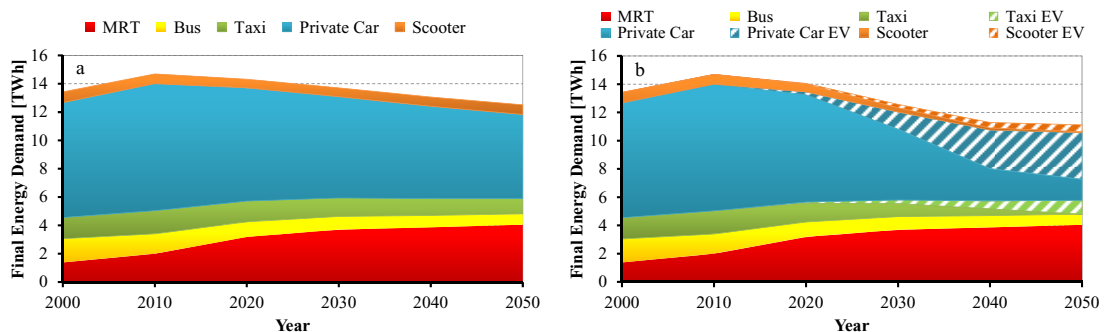


Fig. 3. (a) Final energy demand of passenger transport in the baseline scenario: Because of the higher efficiency of internal combustion engines and a weak growth of motor vehicles, there is a continuous decline until 2050. (b) Final energy demand of passenger transport in the EV scenario: By integrating electric vehicles, the final energy demand can be reduced significantly. The reasons for this are higher levels of energy efficiency in electric drive trains.

Total energy consumption consisting of fossil fuels and electricity has been rising from 13.4 TWh in 2000 to 14.7 TWh in 2010 for the baseline scenario in Fig. 3 (a). Since then, there is a decline to 12.5 TWh in the year 2050 due to the higher efficiency of combustion engines and a relatively small growth of motorised vehicles. In contrary, the final energy demand for the mass rapid transport (MRT)

system shows a strong increase. Especially in the model period from 2010 to 2020 a sharp rise of energy consumption from 2.0 TWh to 3.2 TWh can be observed. This is caused by doubling the MRT length in this decade and the aim of the Land Transport Authority (LTA) to increase the percentage of passengers using public transportation (modal split of public passenger transportation) significantly [7].

As shown in Fig. 3 (b), the integration of electric vehicles is an effective approach to lower the final energy demand of the passenger transportation sector in Singapore considerably. Consumptions dropped from 14.7 TWh in 2010 to 11.1 TWh in 2050. This is caused by a higher level of energy efficiency in electric drive trains. While MRT and buses are based on the same technology as predicted in the baseline scenario, taxis, scooters and private cars are substituted step by step by electric vehicles. Singapore's Taxi and scooter fleets are expected to be fully electrically driven in 2050, whereas the share of combustion engine driven private cars is still only about 25 %.

While the final energy demand for passenger transportation drops over the model horizon, the overall electricity demand is rising. Without electromobility the electricity demand in 2050 amounts to 142 TWh, whereas the electricity consumption with electromobility integration amounts to approximately 147 TWh. Summing up, there is nearly no difference in electricity generation detectable in the year 2050. The primary energy demand for the electricity generation and the passenger transportation together is about 178 TWh both for the modelled PV and EV scenario in the year 2050.

Finally, it is expedient to investigate the impact of electromobility on total CO₂ emissions in Singapore (Fig. 4).

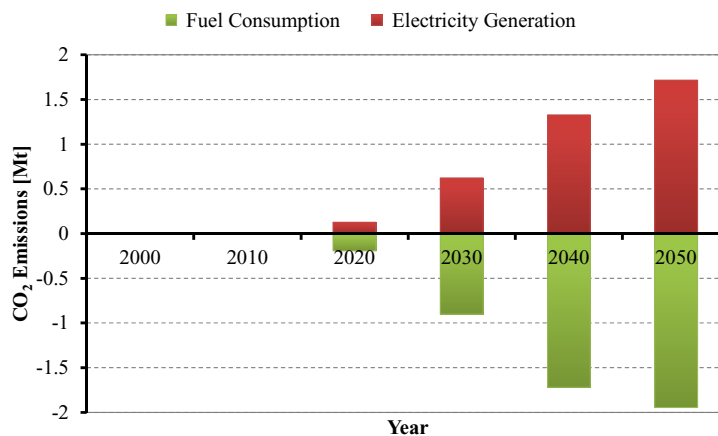


Fig. 4. Impact of EV integration on CO₂ emissions caused by fuel consumption and electricity generation: The reduction of local CO₂ emissions is nearly completely compensated by additional global CO₂ emissions caused by electricity generation. Based on the assumed grid mix, there is no significant improvement concerning Singapore's CO₂ balance.

The integration of electromobility in Singapore causes on the one hand a reduction of local emissions through less fuel consumption and on the other hand more emissions in the electricity generation through higher power demand. Taking Fig. 4 into consideration, it can be seen, that there is a small overall reduction in CO₂ emissions in all model periods. However, the major reduction accounts for 0.39 Mt (1.2%) in 2040. In the year 2050 there is only a decline of 0.23 Mt (0.6%). The lower overall reduction is caused by higher efficiency factors of combustion engine vehicles in 2050 compared to 2040 and similar specific emissions of the grid mix.

3.3. Moderate increase of electricity demand due to energy efficiency measures

The last analysed efficiency scenario is based on a much more moderate increase of the Singapore's electricity demand compared to the previous scenarios. This projection additionally takes into account potential energy efficiency measures which can lessen the electricity demand in Singapore considerably.

The development of the electricity generation in Singapore until the year 2050 is shown in Fig. 5 (a). The simulated electricity demand in 2050 accounts for about 82 TWh. Thus, the electricity demand per capita in the year 2050 will add up to 11,000 kWh. Therefore, a higher percentage of electricity generation by solar PV is detectable at the end of the model horizon (48 %). As projected before, PV power feed in Singapore could reach 40 TWh in 2050.

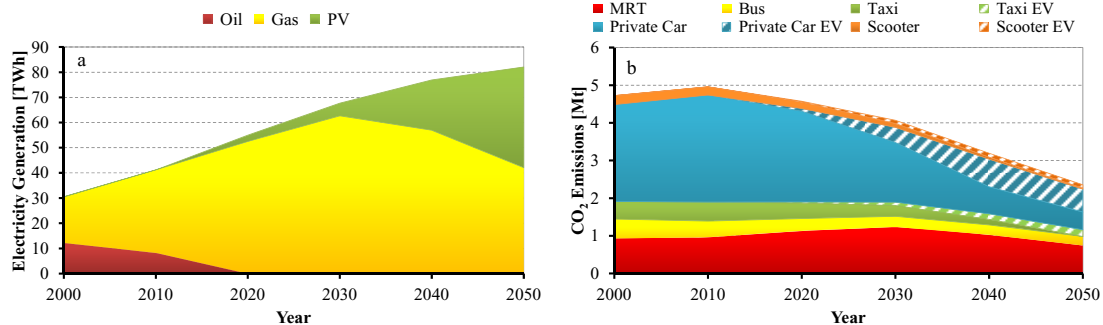


Fig. 5. (a) Electricity generation in the efficiency scenario: The much lower electricity demand compared to the previous baseline scenario results in a significant higher percentage of electricity generated by photovoltaics. (b) CO₂ emissions of the passenger transport in the efficiency scenario: Rising efficiencies of vehicles and power plants together with the integration of electric vehicles lead to declining overall CO₂ emissions as from 2010.

Figure 5 (b) shows the simulated results for CO₂ emissions of the Singapore's passenger transport sector in the model periods considered. The distribution of conventional and electrical cars over the model horizon is the same as predicted in the PV or EV scenario. From 2000 to 2010 overall carbon dioxide emissions have increased from 4.7 Mt to about 5 Mt. Then a continuous decrease to 2.3 Mt compared to 2010 occurs until the year 2050. This is on the one hand due to the higher efficiency of combustion engines and on the other hand due to assumed energy efficiency measures in the Singapore's energy sector. As this study focuses on the effects of the integration of PV and electric vehicles, other efficiency improvements (buildings etc.) are only indirectly simulated by the above mentioned electricity consumption per capita.

As a final point, it is important to investigate the development of Singapore's total electricity generation capacity in each model period until the year 2050 (Fig. 6). New electricity generation capacity of gas, oil and PV power plants installed in each model period is considered as well as still existing past investments. According to the calculations in TIMES, the total installed electricity generation capacity in Singapore is rising from about 10 GW today to about 50 GW in the year 2050.

As existing oil power plants are expected to be in operation only until their decommissioning, no new capacity is constructed as of the year 2010. According to the Statement of Opportunities of the Energy Market Authority (EMA), a minimum reserve margin of 30% above annual peak is required in Singapore.

In the model period from 2010 to 2020 a much higher reserve margin of about 70% is given [3]. For this reason, no further gas power plants are coming into operation. After the year 2020 a steady increase of generation capacity in terms of gas power plants appears. This development is essential in order to cover the peak demand.

Without adequate storage systems, PV capacity can only contribute to save fossil fuels due to its intermittent nature and non-availability during night-times. However, Singapore's PV capacity in the year 2050 could be about 32 GW or 65% of total installed electricity generation capacity.

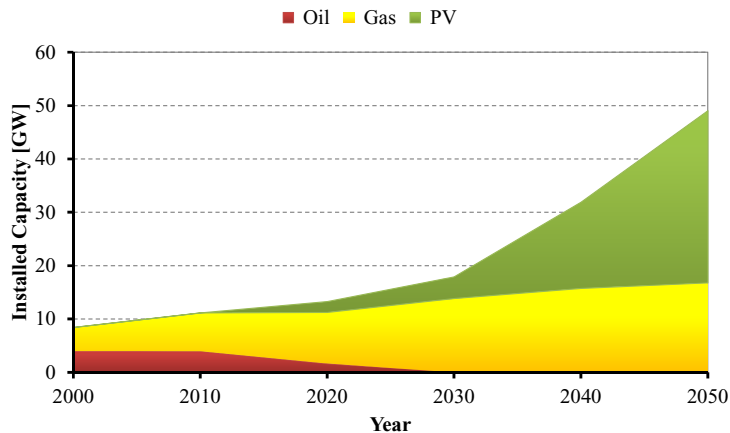


Fig. 6. Electricity generation capacity in Singapore in the efficiency scenario: The increase in electricity demand results in a strong rise of installed generation capacity from solar PV. To meet Singapore's future electricity demand, the generation capacity of gas and PV power plants have to be increased dramatically (50 GW in 2050), especially due to the intermittent nature of solar electricity generation.

4. Conclusion

This paper investigates the impacts of photovoltaics and electromobility on Singapore's energy sector. In a first step, a comparison between the baseline and the PV scenario is conducted. As a major result, PV as a fuel saving technology can lower both Singapore's CO₂ emissions and primary energy demand. Thus, Singapore is expected to reduce import dependencies on fossil fuels from its neighbouring countries.

Secondly, based on the PV scenario, the integration of electromobility into the Singaporean passenger transport sector is discussed (EV scenario). According to the simulation in TIMES, there is just a slight reduction in overall CO₂ emissions compared to the PV scenario.

Lastly, energy efficiency measures in Singapore are considered in the simulated efficiency scenario. Consequently, PV is able to reach a much higher share in the electricity generation.

Through an even stronger expansion of PV electricity generation or exploitation of alternative renewable energies (tidal energy systems, wave energy systems etc.), electromobility could make a better

contribution to a sustainable economy. As shown in the efficiency scenario, the same goal can be achieved by increasing the overall efficiency or reducing total electricity demand.

References

- [1] The Worldbank. *Singapore Data and Statistics*. URL <http://data.worldbank.org>; 2011
- [2] Asia Pacific Energy Research Centre (APERC). *APEC Energy Overview 2010*. Tokyo; 2010
- [3] Energy Market Authority (EMA). *Data and Statistics*. URL <http://www.ema.gov.sg>; 2011
- [4] International Energy Agency (IEA). *Projected Costs of Generating Electricity*. Paris; 2010
- [5] PA Consulting Group. *Energy Market Authority of Singapore*. London; 2010
- [6] Luther J, Aberle A, Reindl T, Mhaisalkar S, Koh K, Jadhav N, Zhang J, Yao K. *Solar Energy Technology Primer: A Summary*. Singapore; 2011
- [7] Land Transport Authority (LTA). *LTMASERPLAN*. Singapore; 2008